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Search for supersymmetry in final states with photons and missing transverse momentum in proton-proton collisions at 13 TeV



The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

ABSTRACT: Results are reported of a search for supersymmetry in final states with photons and missing transverse momentum in proton-proton collisions at the LHC. The data sample corresponds to an integrated luminosity of 35.9 fb^{-1} collected at a center-of-mass energy of 13 TeV using the CMS detector. The results are interpreted in the context of models of gauge-mediated supersymmetry breaking. Production cross section limits are set on gluino and squark pair production in this framework. Gluino masses below 1.86 TeV and squark masses below 1.59 TeV are excluded at 95% confidence level.

KEYWORDS: Hadron-Hadron scattering (experiments), Supersymmetry

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1 Introduction

Supersymmetry (SUSY) and the Minimal Supersymmetric Standard Model [1–6] are extensions of the standard model (SM) that provide explanations for several outstanding issues with the SM. In particular, SUSY addresses the large quantum corrections to the mass term in the Higgs potential [7] and provides a viable dark matter candidate [8, 9]. Models with general gauge-mediated (GGM) SUSY breaking [10–17] have the additional benefit of naturally suppressing flavor violations in the SUSY sector. GGM models can have a wide range of features but typically result in final states that include the gravitino (\tilde{G}) as the lightest supersymmetric particle (LSP). The next-to-lightest supersymmetric particle (NLSP) in these models is often taken to be a neutralino ($\tilde{\chi}_1^0$), which is a mixture of the bino, neutral wino, and neutral higgsinos. The conservation of R parity [18] implies that the gravitino is stable and remains undetected. Therefore, proton-proton (pp) collisions that produce SUSY particles will have an imbalance in the total observed transverse momentum, referred to as missing transverse momentum \vec{p}_T^{miss} and defined as the negative vector sum of the transverse momenta of all visible particles in an event. Its magnitude is referred to as p_T^{miss} . If the composition of the neutralino NLSP is primarily bino-like, its main decay will be to a gravitino and a photon (γ), resulting in final states with significant missing transverse momentum and one or more photons.

This paper presents a search for GGM SUSY in final states involving two photons and missing transverse momentum. The data sample, corresponding to an integrated luminosity of 35.9 fb^{-1} of pp collisions at a center-of-mass energy $\sqrt{s} = 13 \text{ TeV}$, was collected with the CMS detector in 2016. The analysis described here achieves a substantial improvement

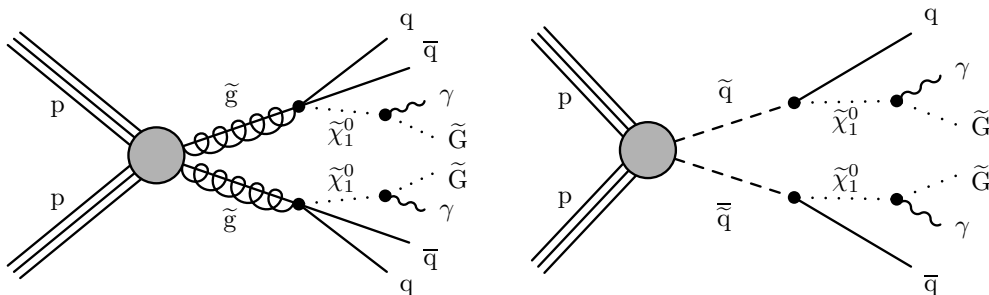


Figure 1. Diagrams showing the production of signal events in the collision of two protons (p). In gluino (\tilde{g}) pair production in the T5gg simplified model (left), the gluino decays to a quark-antiquark pair ($q\bar{q}$) and a neutralino ($\tilde{\chi}_1^0$). In squark (\tilde{q}) pair production in the T6gg simplified model (right), the squark decays to a quark and a neutralino. In both cases, the neutralino subsequently decays to a photon (γ) and a gravitino (\tilde{G}).

in sensitivity compared to the search performed by the CMS Collaboration on the smaller 2015 data set [19] and is comparable in sensitivity to similar searches from the ATLAS Collaboration [20, 21].

Two simplified model frameworks [22–26] are used for the interpretation of the results. The T5gg model assumes gluino (\tilde{g}) pair production and the T6gg model assumes squark (\tilde{q}) pair production. The models assume a 100% branching fraction for the gluinos and squarks to decay as shown in figure 1. The squarks in the T6gg model can be either first or second generation. We assume a 100% branching fraction for the NLSP neutralino to decay to a nearly massless gravitino and a photon, $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$, resulting in characteristic events with large p_T^{miss} and two photons. In order for the analysis to be as model independent as possible, we choose not to define the signal region using any hadronic variables such as jet multiplicity or the scalar sum of the transverse momentum of the jets.

Standard model processes such as direct diphoton production or events with jets produced through the strong interaction, referred to as quantum chromodynamics (QCD) multijet events, can result in events with two photons. If the hadronic activity in the event is poorly measured, these processes can mimic the signal topology even though they lack genuine p_T^{miss} . For the case of QCD multijet events, there may be real photons in the event, or jets rich in electromagnetic (EM) energy that are misreconstructed as photons. Events with genuine p_T^{miss} also contribute to the composition of the candidate sample. These events are mainly from $W\gamma$ and $W+\text{jet(s)}$ production, where an electron is misidentified as a photon in $W \rightarrow e\nu$ decays. A smaller background arises from $Z\gamma\gamma$ events where the Z boson decays to two neutrinos, $Z \rightarrow \nu\bar{\nu}$.

2 Detector, data, and simulated samples

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker covering the pseudorapidity region $|\eta| < 2.5$, as well as a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorime-

ter (HCAL), each composed of a barrel and two endcap regions and covering the range $|\eta| < 3.0$. Forward calorimeters extend the coverage up to $|\eta| < 5.0$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid and cover the range $|\eta| < 2.4$. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [27].

Events of interest are selected using a two-tiered trigger system [28]. The first level is composed of custom hardware processors and uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing. This trigger reduces the event rate to around 1 kHz before data storage. This analysis used a diphoton trigger to collect the data. The trigger requires a leading (subleading) photon with transverse momentum $p_T > 30$ (18) GeV, and a combined invariant mass $m_{\gamma\gamma} > 95$ GeV. The photons are also required to pass isolation and cluster shape requirements.

Monte Carlo (MC) simulations are used for several purposes in this analysis. Simulations of the signal processes are used to determine signal efficiencies; background process simulation is used for validation of the analysis performance and to model the contribution from $Z\gamma\gamma \rightarrow \nu\bar{\nu}\gamma\gamma$ events. The event generator MADGRAPH5_aMC@NLO 2.3.3 [29] is used to simulate the signal samples at leading order. The background samples are generated at next-to-leading order using MADGRAPH5_aMC@NLO 2.4.2. For both signal and background processes, the parton showering, hadronization, SUSY particle decays, multiple-parton interactions, and the underlying event are described by the PYTHIA 8.212 [30] program with the CUETP8M1 [31] generator tune. The signal samples are generated with either two gluinos or two squarks and up to two additional partons in the matrix element calculation. The parton distribution functions (PDFs) are obtained from the NNPDF3.0 [32] set. For the background processes, the detector response is simulated using GEANT4 [33], while the CMS fast simulation [34, 35] is used for the signal events. For both signal and background simulated events, additional pp interactions (pileup) are generated with PYTHIA and superimposed on the primary collision process. The simulated events are reweighted to match the pileup distribution observed in data.

The signal events were generated using the T5gg and T6gg simplified models and are characterized by the masses of the particles in the decay chain. For the gluino (squark) mass we simulate a range of values from 1.4 to 2.5 (1.2 to 2.0) TeV in steps of 50 GeV. These mass ranges were selected to overlap and expand upon the mass ranges excluded by previous searches [19, 20]. The neutralino masses range from 10 GeV up to the mass of the gluino or squark. The cross sections are calculated at next-to-leading-order (NLO) accuracy including the resummation of soft gluon emission at next-to-leading-logarithmic (NLL) accuracy [36–40], with all the unconsidered sparticles assumed to be heavy and decoupled. The uncertainties in the cross sections are calculated as described in ref. [41].

3 Event selection

Photon, electron, muon, charged and neutral hadron candidates are reconstructed with the particle-flow event algorithm [42], which reconstructs particles based on information from all detector subsystems. The energy of photons is directly obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

Photon candidates are required to satisfy a series of identification criteria to ensure a high purity [43]. The shape of the energy deposit in the ECAL must be consistent with that of an EM shower, and the amount of energy present in the corresponding region of the HCAL must not exceed 5% of the ECAL energy, since EM showers are expected to be contained almost entirely within the ECAL. To ensure high trigger efficiency, we require all photons to satisfy $p_T > 40$ GeV. Because the SUSY signal models used in this analysis produce photons primarily in the central region of the detector and because the magnitude of the background increases considerably at high $|\eta|$, we consider only photons within the barrel fiducial region of the detector ($|\eta| < 1.44$).

To suppress quark and gluon jets that mimic photons, photon candidates are required to be isolated from other reconstructed particles. Separate requirements are made on the scalar p_T sums of charged and neutral hadrons and EM objects in a cone of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \equiv 0.3$ around the photon candidate. Each p_T sum is corrected for the effect of pileup, and in each case the momentum of the photon candidate itself is excluded. We further require that the photon candidate has no pixel detector track seed, to distinguish the candidate from an electron.

For the purpose of defining the various control regions used in the analysis, we apply an additional set of selection criteria. A misidentified “fake” photon (f) is defined as a photon candidate that satisfies looser requirements on photon isolation and neutral-hadron isolation and fails either the shape requirement for the ECAL clusters or the charged-hadron isolation requirement. In order to ensure that misidentified photons do not differ too much from our photon selection, upper limits are applied to both the charged-hadron isolation and cluster shape requirements. Importantly, because of the large amount of hadronic activity expected in our SUSY signal events, it is possible that real photons from the decay of a neutralino could fail the charged-hadron isolation requirement and therefore fall into the misidentified photon category. In order to avoid this potential signal contamination from SUSY events in the control regions, we additionally require that misidentified photons satisfy $R_9 < 0.9$, where R_9 is defined as the ratio of the energy deposited in a 3×3 array of ECAL crystals to the total energy in the cluster [43]. Real photons have values of R_9

close to unity, so by requiring $R_9 < 0.9$ we ensure that real photons from a possible SUSY signal will not enter our control regions.

Because of the similarity of the ECAL response to electrons and photons, $Z \rightarrow ee$ events are used to measure the photon identification efficiency. The selection of electron candidates is identical to that of photons, with the exception that the candidate is required to be matched to a pixel detector seed consistent with a track, to ensure that the electron selection is orthogonal to that of photons. The photon efficiency is measured via the tag-and-probe method [43]. The ratio of the observed to simulated efficiency is found to be consistent with unity and independent of p_T and η . The efficiency of the pixel detector seed veto for photons is measured in $Z \rightarrow \mu\mu\gamma$ events and is found to agree between data and simulation.

Events are then assigned to one of four mutually exclusive categories depending on the selection of their highest p_T EM objects: $\gamma\gamma$, ee , ff , and $e\gamma$. The two EM objects are required to be separated by $\Delta R > 0.6$. Finally, because of the trigger requirements described in section 2, the invariant mass of the two EM objects is required to be greater than 105 GeV.

In addition to the requirements already described, any event with a muon satisfying $p_T > 25$ GeV and $|\eta| < 2.4$ as well as track quality and isolation requirements is vetoed. Similarly, we veto events with any additional electrons satisfying $p_T > 25$ GeV, $|\eta| < 2.5$, and signal shape and isolation requirements.

Events in the candidate $\gamma\gamma$ sample are divided into the low- p_T^{miss} control region ($p_T^{\text{miss}} < 100$ GeV) and the high- p_T^{miss} signal region ($p_T^{\text{miss}} > 100$ GeV). The signal region is further divided into six p_T^{miss} bins that were chosen such that there is a sufficient number of events from the ff control sample in each bin.

4 Estimation of backgrounds

As described in section 1, there are three primary backgrounds to this analysis. QCD processes such as multijet production can emulate the signal topology if the hadronic activity in the event is mismeasured. A second background arises from electroweak (EWK) processes that have genuine p_T^{miss} from the production of neutrinos. There is also a small contribution from $Z\gamma\gamma \rightarrow \gamma\gamma\nu\bar{\nu}$ events.

The contribution from the QCD background is estimated from the observed data using the ff control sample. The ratio of the event yield in the candidate $\gamma\gamma$ sample to that in the ff sample is constructed as a function of p_T^{miss} . More ff events are observed at high p_T^{miss} relative to the $\gamma\gamma$ sample. Different functional forms were investigated to model the p_T^{miss} dependence, and an exponential function was found to describe the data the best. We fit the $\gamma\gamma$ to ff ratio in the $p_T^{\text{miss}} < 100$ GeV control region. The predicted number of QCD background events (N_{QCD}^i) in bin i of the signal region is then given by the following equation, where N_{ff}^i is the number of observed ff events and g_{ave}^i is the average value of the fit function $g(p_T^{\text{miss}})$ in that bin:

$$N_{\text{QCD}}^i = g_{\text{ave}}^i N_{ff}^i \quad (4.1)$$

In order to set a systematic uncertainty on the method, we derive a second QCD background prediction by noting that the p_T^{miss} distribution of the ff control sample is dependent on the R_9 requirement on the misidentified photons. An alternate ff control sample is built using photon candidates that satisfy all of the requirements for misidentified photons as outlined in section 3, with the exception that the R_9 requirement is reversed. In the $p_T^{\text{miss}} < 100$ GeV control region, we perform an exponential fit to the ratio of the event yield in the high- R_9 ff sample to that of the nominal, low- R_9 ff sample. This function ($h(p_T^{\text{miss}})$) represents the correction required to account for the effect of the R_9 selection on the p_T^{miss} distribution. The size of the correction is between 20 and 40% in the $p_T^{\text{miss}} > 100$ GeV signal region. Multiplying the number of low- R_9 ff events observed in the signal region by this function gives a proxy high- R_9 ff sample.

$$N_{\text{proxy}}^i = h_{\text{ave}}^i N_{ff}^i \quad (4.2)$$

For $p_T^{\text{miss}} < 100$ GeV, the ratio of the p_T^{miss} distribution in the $\gamma\gamma$ sample to that of the proxy ff sample is fit to a constant C . We multiply this constant value by the proxy ff yield in the signal region to get a second prediction for the QCD background in bin i .

$$N_{\text{QCD}}^i = C N_{\text{proxy}}^i \quad (4.3)$$

The two background estimation methods give values that are consistent within the uncertainties. All three of the fits used in the two methods are found to represent the data well in the low- p_T^{miss} control region. Several studies were performed to verify the procedure, including using a mixed- R_9 ff sample with one misidentified photon satisfying $R_9 > 0.9$ and one satisfying $R_9 < 0.9$ to confirm that the exponential fit continues to accurately describe the mixed- R_9 ff to nominal ff ratio in the high- p_T^{miss} signal region. As an additional check, a control sample with one photon and one misidentified photon was used as a proxy for the $\gamma\gamma$ candidate sample in a closure test of the method up to $p_T^{\text{miss}} = 250$ GeV. At larger values of p_T^{miss} , there is the potential for signal contamination in the γf control sample.

Another background for this analysis comes from EWK processes with genuine p_T^{miss} . This background primarily involves $W\gamma$ and W +jets events where the W decays to an electron and a neutrino and the electron is misidentified as photon. This leads to final states with photons and significant p_T^{miss} . To obtain an estimate of the EWK background in the signal region, the mass peaks from the Z boson in the ee control sample and the $e\gamma$ control sample are modeled using an extended likelihood fit for the signal plus background hypothesis. The rate at which electrons are misidentified as photons ($f_{e\rightarrow\gamma}$) is calculated using the signal fit integrals $N_{e\gamma}$ and N_{ee} for each sample. These can be expressed in terms of the number of true Z bosons, N_Z^{True} : $N_{ee} = (1 - f_{e\rightarrow\gamma})^2 N_Z^{\text{True}}$ and $N_{e\gamma} = 2f_{e\rightarrow\gamma}(1 - f_{e\rightarrow\gamma})N_Z^{\text{True}}$. The factor of 2 in $N_{e\gamma}$ occurs because either electron in the event could be misidentified as a photon.

Taking the ratio of these two values, we find that the misidentification rate is given by $f_{e\rightarrow\gamma} = N_{e\gamma} / (2N_{ee} + N_{e\gamma})$. The misidentification rate is calculated as a function of several kinematic variables, including the vertex multiplicity and p_T^{miss} of the event and the p_T of the EM objects. A 30% uncertainty is applied to cover the observed dependencies. The

p_T^{miss} bin (GeV)	Expected QCD	Stat. uncert.	Fit uncert.	Cross check uncert.
100 – 115	99.0	+7.2, –6.7	± 1.8	± 9.9
115 – 130	32.8	+4.2, –3.7	± 0.7	± 5.5
130 – 150	18.8	+3.2, –2.7	± 0.5	± 4.0
150 – 185	9.9	+2.3, –1.9	± 0.3	± 2.8
185 – 250	3.1	+1.3, –0.9	± 0.1	± 1.5
≥ 250	1.0	+0.8, –0.5	± 0.1	± 0.8

Table 1. Event yield and statistical and systematic uncertainties (in numbers of events) of the QCD background estimation for each signal p_T^{miss} bin for 35.9 fb^{-1} of data at 13 TeV.

final EWK background prediction is given by scaling the number of events in the $e\gamma$ control sample by the factor $f_{e\gamma \rightarrow \gamma\gamma} = f_{e \rightarrow \gamma} / (1 - f_{e \rightarrow \gamma}) = (2.6 \pm 0.8)\%$.

The irreducible $Z\gamma\gamma$ background is modeled via simulation. A 50% uncertainty is applied to conservatively cover the effects from the statistical uncertainty of the MC sample, the PDF uncertainty in the cross section, NNLO corrections in the simulation, and any other sources of potential mismodeling.

5 Sources of systematic uncertainty

Systematic uncertainties are calculated for each contribution to the total background prediction. In addition, systematic uncertainties are assigned for the signal efficiency and the integrated luminosity. The value of each uncertainty and the method used to calculate it are described below.

The largest uncertainties in the background prediction come from uncertainties associated with the QCD background estimate. The magnitude of each uncertainty is shown in table 1 for the six signal bins. The statistical uncertainty from the ff control sample ranges from 7 to 79% in the signal region. The uncertainty obtained from propagating the errors in the fit parameters to the final prediction is between 2 and 5%. Finally, as described in section 4, a systematic uncertainty in the fitting procedure is calculated by comparing the primary prediction to the cross check prediction derived using the high- R_9 ff sample. The systematic uncertainty is taken as the difference between the two methods or the uncertainty in that difference, whichever is larger, and ranges between 10 and 83% in the signal region.

Uncertainties in the EWK background prediction include the statistical uncertainty from the $e\gamma$ control sample and the 30% uncertainty in the rate at which electrons are misidentified as photons. The statistical uncertainty is less than 9% in each of the six signal bins.

There are also several uncertainties associated with the signal efficiency. The statistical uncertainty from the size of the T5gg or T6gg signal scans ranges from 2 to 44% depending on the mass bin. The PDF uncertainties in the cross sections for signal simulation are between 19 and 35% and are taken from ref. [41]. Other uncertainties include how well the jet energy scale is known (1 to 30%) and the uncertainty in the photon identification efficiency (2.5%). The uncertainty in the integrated luminosity of the data sample is 2.5% [44].

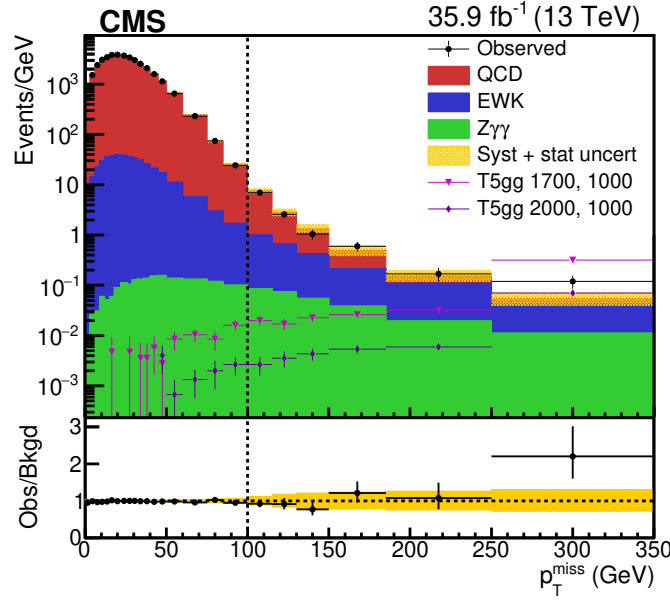


Figure 2. The top panel shows the observed p_T^{miss} distribution in data (black points) and predicted background distributions prior to the fit described in the text. The vertical line marks the boundary between the control region ($p_T^{\text{miss}} < 100$ GeV) and the signal region ($p_T^{\text{miss}} > 100$ GeV). The last bin is the overflow bin and includes all events with $p_T^{\text{miss}} > 250$ GeV. The QCD background is shown in red, the EWK background is shown in blue, and the $Z\gamma\gamma$ background is shown in green. The p_T^{miss} distribution shown in pink (purple) corresponds to the T5gg simplified model with $m_{\tilde{g}} = 1700$ (2000) GeV and $m_{\tilde{\chi}_1^0} = 1000$ GeV. The p_T^{miss} distributions from the T6gg simplified model are similar to the T5gg distributions shown here. The bottom panel shows the ratio of observed events to the expected background. The error bars on the ratio correspond to the statistical uncertainty in the number of observed events. The shaded region corresponds to the total uncertainty in the background estimate.

6 Results

We determine 95% confidence level (CL) upper limits on gluino pair production and squark pair production cross sections using the modified frequentist CL_s method [45, 46]. The test statistic is an LHC-style profile likelihood ratio [47], and its distribution is determined using the asymptotic approximation [48]. The likelihood function is constructed from the background and signal p_T^{miss} distributions across the six bins described in section 4. The systematic uncertainties described in section 5 are included in the test statistic as constrained nuisance parameters. Systematic uncertainties which directly affect the yields of processes are assumed to follow a log-normal probability distribution, while statistical uncertainties from the limited size of the control samples and the signal MC samples are modeled using gamma probability distributions.

The full background prediction and the measured p_T^{miss} distribution prior to the fit are shown in figure 2. The expected and observed numbers of events for each bin in the signal region are shown in table 2 for the pre-fit distributions and table 3 for the post-fit distributions. Notably, in the last bin we observe 12 events and expect $5.4_{-1.5}^{+1.6}$ background

p_T^{miss} bin (GeV)	QCD	EWK	$Z\gamma\gamma$	Total background	Observed
100 – 115	99 ± 12	13.7 ± 4.2	1.3 ± 0.6	114 ± 13	105
115 – 130	$32.8^{+7.0}_{-6.7}$	9.0 ± 2.7	1.1 ± 0.6	$42.9^{+7.5}_{-7.3}$	39
130 – 150	$18.8^{+5.1}_{-4.9}$	7.4 ± 2.3	1.1 ± 0.6	$27.3^{+5.6}_{-5.4}$	21
150 – 185	$9.9^{+3.6}_{-3.4}$	6.1 ± 1.9	1.3 ± 0.7	$17.4^{+4.1}_{-3.9}$	21
185 – 250	$3.1^{+1.9}_{-1.7}$	5.8 ± 1.8	1.3 ± 0.6	$10.2^{+2.7}_{-2.6}$	11
≥ 250	$1.0^{+1.1}_{-0.9}$	3.3 ± 1.1	1.1 ± 0.6	$5.4^{+1.6}_{-1.5}$	12

Table 2. Number of expected background and observed data events with 35.9fb^{-1} of 13 TeV data in the signal region prior to the fit defined in the text. The uncertainty in each expected background yield includes the statistical uncertainty and all of the systematic uncertainties described in section 5 added in quadrature.

p_T^{miss} bin (GeV)	QCD	EWK	$Z\gamma\gamma$	Total background	Observed
100 – 115	92.7 ± 7.9	15.9 ± 3.8	1.6 ± 0.8	110.1 ± 7.4	105
115 – 130	29.7 ± 4.4	10.4 ± 2.5	1.4 ± 0.7	41.5 ± 3.9	39
130 – 150	16.0 ± 3.2	8.5 ± 2.1	1.3 ± 0.7	25.9 ± 3.1	21
150 – 185	9.3 ± 2.7	7.1 ± 1.8	1.6 ± 0.8	18.1 ± 2.6	21
185 – 250	2.6 ± 1.2	6.7 ± 1.6	1.6 ± 0.8	10.9 ± 1.8	11
≥ 250	0.7 ± 0.8	4.0 ± 1.0	1.4 ± 0.7	6.0 ± 1.2	12

Table 3. Number of expected background and observed data events with 35.9fb^{-1} of 13 TeV data in the signal region after the fit defined in the text. The stated uncertainties are the post-fit uncertainties in each expected background yield.

events (pre-fit). The significance of the observed data after the fit across all six bins of the signal region is calculated using the likelihood ratio test for each mass pair value of $m_{\tilde{\chi}_1^0}$ versus $m_{\tilde{g}}$ or $m_{\tilde{\chi}_1^0}$ versus $m_{\tilde{q}}$ for the T5gg and T6gg models, respectively. The significance does not strongly depend on the SUSY masses, and for all masses in both models, the significance is found to correspond to between 2.35 and 2.45 standard deviations. Several studies were performed to characterize the fit and the excess in the final p_T^{miss} bin and to ensure that the statistical treatment of the data is robust. In particular, the pre- and postfit distributions were checked to make sure that the pulls are consistent within the uncertainties.

In figure 3 we present 95% CL upper limits on the gluino and squark pair production cross sections as a function of the mass pair values for the two models considered in this analysis. From the NLO+NLL predicted signal cross sections and their uncertainties we derive contours representing lower limits in the SUSY mass plane. We also show expected limit contours based on the expected experimental cross section limits and their uncertainties. For values of the neutralino mass between 500 and 1500 GeV, we expect to exclude gluino masses up to 2.02 TeV and squark masses up to 1.74 TeV. This is an improvement

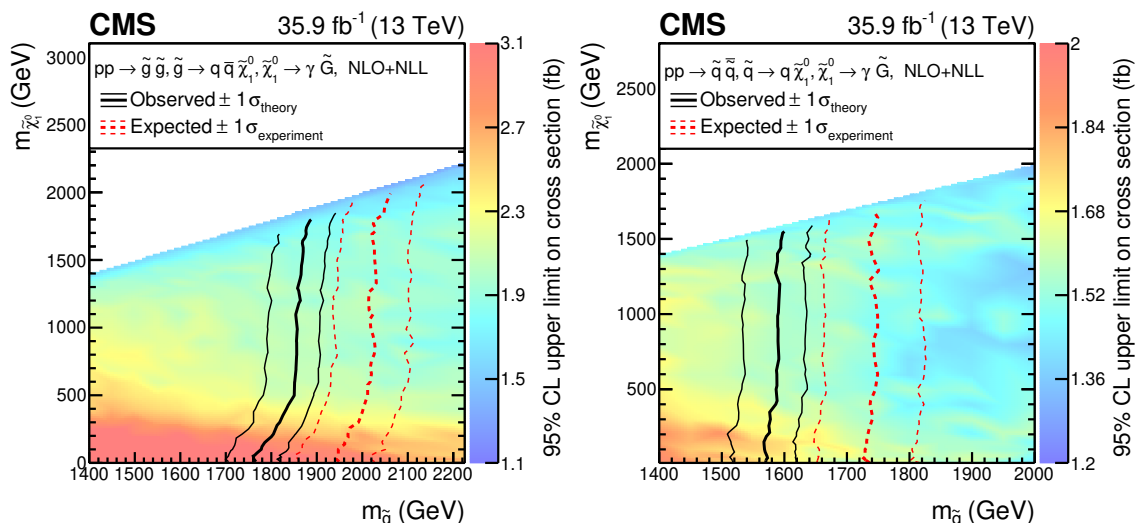


Figure 3. The 95% confidence level upper limits on the gluino (left) and squark (right) pair production cross sections as a function of gluino or squark and neutralino masses. The contours show the observed and expected exclusions assuming the NLO+NLL cross sections, with their one standard deviation uncertainties.

of approximately 400 and 300 GeV, respectively, upon the reach of the previous CMS result [19]. We observe exclusions for gluino masses up to 1.86 TeV and squark masses up to 1.59 TeV. The observed exclusions are lower than the expected exclusions because of the observed excess in the data.

7 Summary

The results of a search for general gauge-mediated supersymmetry breaking in proton-proton collisions with two photons and missing transverse momentum in the final state are reported. The analysis was performed using data corresponding to 35.9 fb^{-1} of integrated luminosity, recorded with the CMS detector in 2016 at a proton-proton center-of-mass energy of 13 TeV. An excess of events corresponding to 2.4 standard deviations is observed. Limits are determined on the masses of supersymmetric particles in two simplified models using data-driven background estimation methods and NLO+NLL signal cross section calculations.

In both models, the next-to-lightest supersymmetric particle is the neutralino, which decays with a 100% branching fraction to a photon and a gravitino, the lightest supersymmetric particle. The first simplified model assumes gluino pair production, with each gluino decaying to a neutralino and quarks. The second simplified model assumes squark pair production, with each squark decaying to a quark and a neutralino. The expected limits on gluino and squark masses, for the respective models, are 2.02 and 1.74 TeV at 95% confidence level. This is an increase in sensitivity of more than 300 GeV for each model with respect to the analysis performed with 2.3 fb^{-1} of integrated luminosity collected using the CMS detector in 2015. The observed exclusions are for gluino masses less than 1.86 TeV

and squark masses less than 1.59 TeV, where the difference between the expected and observed exclusions is driven by the excess observed in the data. The analysis described in this paper improves the observed limits by 210 GeV for gluino masses and 220 GeV for squark masses with respect to the previous CMS result.

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tion, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonatobis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

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References

- [1] C.R. Nappi and B.A. Ovrut, *Supersymmetric extension of the $SU(3) \times SU(2) \times U(1)$ model*, *Phys. Lett.* **113B** (1982) 175 [[INSPIRE](#)].
- [2] M. Dine and W. Fischler, *A phenomenological model of particle physics based on supersymmetry*, *Phys. Lett.* **110B** (1982) 227 [[INSPIRE](#)].
- [3] L. Álvarez-Gaumé, M. Claudson and M.B. Wise, *Low-energy supersymmetry*, *Nucl. Phys. B* **207** (1982) 96 [[INSPIRE](#)].
- [4] M. Dine and A.E. Nelson, *Dynamical supersymmetry breaking at low-energies*, *Phys. Rev. D* **48** (1993) 1277 [[hep-ph/9303230](#)] [[INSPIRE](#)].
- [5] M. Dine, A.E. Nelson and Y. Shirman, *Low-energy dynamical supersymmetry breaking simplified*, *Phys. Rev. D* **51** (1995) 1362 [[hep-ph/9408384](#)] [[INSPIRE](#)].
- [6] M. Dine, A.E. Nelson, Y. Nir and Y. Shirman, *New tools for low-energy dynamical supersymmetry breaking*, *Phys. Rev. D* **53** (1996) 2658 [[hep-ph/9507378](#)] [[INSPIRE](#)].
- [7] R. Barbieri and G.F. Giudice, *Upper bounds on supersymmetric particle masses*, *Nucl. Phys. B* **306** (1988) 63 [[INSPIRE](#)].
- [8] H. Goldberg, *Constraint on the photino mass from cosmology*, *Phys. Rev. Lett.* **50** (1983) 1419 [*Erratum ibid.* **103** (2009) 099905] [[INSPIRE](#)].
- [9] J.R. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive and M. Srednicki, *Supersymmetric relics from the big bang*, *Nucl. Phys. B* **238** (1984) 453 [[INSPIRE](#)].
- [10] S. Dimopoulos, G.F. Giudice and A. Pomarol, *Dark matter in theories of gauge-mediated supersymmetry breaking*, *Phys. Lett. B* **389** (1996) 37 [[hep-ph/9607225](#)] [[INSPIRE](#)].
- [11] S.P. Martin, *Generalized messengers of supersymmetry breaking and the sparticle mass spectrum*, *Phys. Rev. D* **55** (1997) 3177 [[hep-ph/9608224](#)] [[INSPIRE](#)].
- [12] E. Poppitz and S.P. Trivedi, *Some remarks on gauge-mediated supersymmetry breaking*, *Phys. Lett. B* **401** (1997) 38 [[hep-ph/9703246](#)] [[INSPIRE](#)].
- [13] P. Meade, N. Seiberg and D. Shih, *General gauge mediation*, *Prog. Theor. Phys. Suppl.* **177** (2009) 143 [[arXiv:0801.3278](#)] [[INSPIRE](#)].

- [14] M. Buican, P. Meade, N. Seiberg and D. Shih, *Exploring general gauge mediation*, *JHEP* **03** (2009) 016 [[arXiv:0812.3668](#)] [[INSPIRE](#)].
- [15] S. Abel, M.J. Dolan, J. Jaeckel and V.V. Khoze, *Phenomenology of pure general gauge mediation*, *JHEP* **12** (2009) 001 [[arXiv:0910.2674](#)] [[INSPIRE](#)].
- [16] L.M. Carpenter, M. Dine, G. Festuccia and J.D. Mason, *Implementing general gauge mediation*, *Phys. Rev. D* **79** (2009) 035002 [[arXiv:0805.2944](#)] [[INSPIRE](#)].
- [17] T.T. Dumitrescu, Z. Komargodski, N. Seiberg and D. Shih, *General messenger gauge mediation*, *JHEP* **05** (2010) 096 [[arXiv:1003.2661](#)] [[INSPIRE](#)].
- [18] G.R. Farrar and P. Fayet, *Phenomenology of the production, decay and detection of new hadronic states associated with supersymmetry*, *Phys. Lett. B* **76** (1978) 37.
- [19] CMS collaboration, *Search for supersymmetry in events with photons and missing transverse energy in pp collisions at 13 TeV*, *Phys. Lett. B* **769** (2017) 391 [[arXiv:1611.06604](#)] [[INSPIRE](#)].
- [20] ATLAS collaboration, *Search for supersymmetry in a final state containing two photons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions at the LHC using the ATLAS detector*, *Eur. Phys. J. C* **76** (2016) 517 [[arXiv:1606.09150](#)] [[INSPIRE](#)].
- [21] ATLAS collaboration, *Search for photonic signatures of gauge-mediated supersymmetry in 13 TeV pp collisions with the ATLAS detector*, *Phys. Rev. D* **97** (2018) 092006 [[arXiv:1802.03158](#)] [[INSPIRE](#)].
- [22] N. Arkani-Hamed et al., *MARMOSSET*, [hep-ph/0703088](#) [[INSPIRE](#)].
- [23] J. Alwall, P. Schuster and N. Toro, *Simplified models for a first characterization of new physics at the LHC*, *Phys. Rev. D* **79** (2009) 075020 [[arXiv:0810.3921](#)] [[INSPIRE](#)].
- [24] J. Alwall, M.-P. Le, M. Lisanti and J.G. Wacker, *Model-independent jets plus missing energy searches*, *Phys. Rev. D* **79** (2009) 015005 [[arXiv:0809.3264](#)] [[INSPIRE](#)].
- [25] LHC NEW PHYSICS WORKING GROUP collaboration, *Simplified models for LHC new physics searches*, *J. Phys. G* **39** (2012) 105005 [[arXiv:1105.2838](#)] [[INSPIRE](#)].
- [26] CMS collaboration, *Interpretation of searches for supersymmetry with simplified models*, *Phys. Rev. D* **88** (2013) 052017 [[arXiv:1301.2175](#)] [[INSPIRE](#)].
- [27] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [[INSPIRE](#)].
- [28] CMS collaboration, *The CMS trigger system*, 2017 *JINST* **12** P01020 [[arXiv:1609.02366](#)] [[INSPIRE](#)].
- [29] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [30] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A brief introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852 [[arXiv:0710.3820](#)] [[INSPIRE](#)].
- [31] CMS collaboration, *Event generator tunes obtained from underlying event and multiparton scattering measurements*, *Eur. Phys. J. C* **76** (2016) 155 [[arXiv:1512.00815](#)] [[INSPIRE](#)].
- [32] NNPDF collaboration, *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040 [[arXiv:1410.8849](#)] [[INSPIRE](#)].

- [33] GEANT4 collaboration, GEANT4 — *a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [INSPIRE].
- [34] CMS collaboration, *The fast simulation of the CMS detector at LHC*, *J. Phys. Conf. Ser.* **331** (2011) 032049 [INSPIRE].
- [35] A. Giammanco, *The fast simulation of the CMS experiment*, *J. Phys. Conf. Ser.* **513** (2014) 022012 [INSPIRE].
- [36] W. Beenakker, R. Hopker, M. Spira and P.M. Zerwas, *Squark and gluino production at hadron colliders*, *Nucl. Phys. B* **492** (1997) 51 [hep-ph/9610490] [INSPIRE].
- [37] A. Kulesza and L. Motyka, *Threshold resummation for squark-antisquark and gluino-pair production at the LHC*, *Phys. Rev. Lett.* **102** (2009) 111802 [arXiv:0807.2405] [INSPIRE].
- [38] A. Kulesza and L. Motyka, *Soft gluon resummation for the production of gluino-gluino and squark-antisquark pairs at the LHC*, *Phys. Rev. D* **80** (2009) 095004 [arXiv:0905.4749] [INSPIRE].
- [39] W. Beenakker, S. Brensing, M. Krämer, A. Kulesza, E. Laenen and I. Niessen, *Soft-gluon resummation for squark and gluino hadroproduction*, *JHEP* **12** (2009) 041 [arXiv:0909.4418] [INSPIRE].
- [40] W. Beenakker et al., *Squark and gluino hadroproduction*, *Int. J. Mod. Phys. A* **26** (2011) 2637 [arXiv:1105.1110] [INSPIRE].
- [41] C. Borschensky et al., *Squark and gluino production cross sections in pp collisions at $\sqrt{s} = 13, 14, 33$ and 100 TeV*, *Eur. Phys. J. C* **74** (2014) 3174 [arXiv:1407.5066] [INSPIRE].
- [42] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, *2017 JINST* **12** P10003 [arXiv:1706.04965] [INSPIRE].
- [43] CMS collaboration, *Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *2015 JINST* **10** P08010 [arXiv:1502.02702] [INSPIRE].
- [44] CMS collaboration, *CMS luminosity measurements for the 2016 data taking period*, *CMS-PAS-LUM-17-001* (2017).
- [45] T. Junk, *Confidence level computation for combining searches with small statistics*, *Nucl. Instrum. Meth. A* **434** (1999) 435 [hep-ex/9902006] [INSPIRE].
- [46] A.L. Read, *Presentation of search results: the CL_s technique*, *J. Phys. G* **28** (2002) 2693 [INSPIRE].
- [47] ATLAS and CMS collaborations, the LHC HIGGS Combination Group, *Procedure for the LHC Higgs boson search combination in Summer 2011*, *CMS-NOTE-2011-005*, *ATL-PHYS-PUB-2011-11* (2011).
- [48] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [Erratum *ibid.* **C 73** (2013) 2501] [arXiv:1007.1727] [INSPIRE].

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, V.M. Ghete, J. Hrubec, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck¹, R. Schöffbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, A. Lelek, M. Pieters, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, J. D'Hondt, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, A. Grebenyuk, A.K. Kalsi, J. Luetic, A. Popov², N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov³, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, K. Piotrkowski, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁵, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote⁴, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

S. Ahuja^a, C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, SandraS. Padula^a

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China

W. Fang⁶, X. Gao⁶, L. Yuan

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, S.M. Shaheen⁷, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang⁷, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang

Tsinghua University, Beijing, China

Y. Wang

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia

J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov⁸, T. Susa

University of Cyprus, Nicosia, Cyprus

M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic

M. Finger⁹, M. Finger Jr.⁹

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

**Academy of Scientific Research and Technology of the Arab Republic of Egypt,
Egyptian Network of High Energy Physics, Cairo, Egypt**

Y. Assran^{10,11}, S. Elgammal¹¹, S. Khalil¹²

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik,
M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén,
K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen,
E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour,
A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles,
J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro¹³, M. Titov

**Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université
Paris-Saclay, Palaiseau, France**

C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, R. Granier de Cassagnac,
I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez, M. Nguyen, C. Ochando,
G. Ortona, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

J.-L. Agram¹⁴, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert,
V. Cherepanov, C. Collard, E. Conte¹⁴, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, M. Jansová,
A.-C. Le Bihan, N. Tonon, P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique
des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut
de Physique Nucléaire de Lyon, Villeurbanne, France**

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse,
H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde,

I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze⁹

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁹

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

A. Albert, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, A. Novak, T. Pook, A. Pozdnyakov, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, A. Sharma, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

G. Flügge, O. Hlushchenko, T. Kress, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁵

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras¹⁶, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁷, A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, N.Z. Jomhari, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, K. Lipka, W. Lohmann¹⁸, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinemann, A. Karavdina, G. Kasieczka, R. Klaner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, C.E.N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, M.A. Harrendorf,

F. Hartmann¹⁵, U. Husemann, I. Katkov², S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Musich, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Weber, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, G. Paspalaki

National and Kapodistrian University of Athens, Athens, Greece

A. Agapitos, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Vellidis

National Technical University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitaras, N. Manthos, I. Papadopoulos, E. Paradas, J. Strogas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Bartók¹⁹, M. Csanad, N. Filipovic, P. Major, K. Mandal, A. Mehta, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²⁰, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi¹⁹, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bahinipati²², C. Kar, P. Mal, A. Nayak²³, S. Roy Chowdhury, D.K. Sahoo²², S.K. Swain

Punjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi, G. Walia

University of Delhi, Delhi, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj²⁴, M. Bharti²⁴, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁴, D. Bhowmik, S. Dey, S. Dutt²⁴, S. Dutta, S. Ghosh, M. Maity²⁵, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar²⁵, M. Sharan, B. Singh²⁴, S. Thakur²⁴

Indian Institute of Technology Madras, Madras, India

P.K. Behera, A. Muhammad

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla, P. Suggsetti

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kotheekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Chenarani²⁶, E. Eskandari Tadavani, S.M. Etesami²⁶, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh²⁷, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, F. Errico^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^a, R. Venditti^a, P. Verwilligen^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,28}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b,29}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b,29}, C. Tuve^{a,b}

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b},
G. Latino, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,30}, G. Sguazzoni^a, D. Strom^a,
L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova ^a, Università di Genova ^b, Genova, Italy

F. Ferro^a, R. Mulargia^{a,b}, E. Robutti^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^a, A. Beschi^b, F. Brivio^{a,b}, V. Ciriolo^{a,b,15}, S. Di Guida^{a,b,15}, M.E. Dinardo^{a,b},
S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a,
D. Menasce^a, F. Monti, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b},
T. Tabarelli de Fatis^{a,b}, D. Zuolo^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. De Iorio^{a,b}, A. Di Crescenzo^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a,
G. Galati^a, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,15}, P. Paolucci^{a,15}, C. Sciacca^{a,b},
E. Voevodina^{a,b}

INFN Sezione di Padova ^a, Università di Padova ^b, Padova, Italy, Università di Trento ^c, Trento, Italy

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, A. Boletti^{a,b}, A. Bragagnolo, R. Carlin^{a,b},
P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a,
F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S.Y. Hoh, S. Lacaprara^a, P. Lujan,
M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, M. Presilla^b, P. Ronchese^{a,b}, R. Rossin^{a,b},
F. Simonetto^{a,b}, A. Tiko, E. Torassa^a, M. Tosi^{a,b}, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

A. Braghieri^a, A. Magnani^a, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b},
C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b},
R. Leonardi^{a,b}, E. Manoni^a, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b},
A. Santocchia^{a,b}, D. Spiga^a

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, L. Bianchini^a, T. Boccali^a, L. Borrello,
R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, F. Fiori^{a,c}, L. Giannini^{a,c}, A. Giassi^a,
M.T. Grippo^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a,

A. Rizzi^{a,b}, G. Rolandi³¹, A. Scribano^a, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b},
A. Venturi^a, P.G. Verdini^a

INFN Sezione di Roma ^a, Sapienza Università di Roma ^b, Rome, Italy

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b}, E. Di Marco^{a,b},
M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b},
F. Pandolfi^a, R. Paramatti^{a,b}, F. Preiato^{a,b}, C. Quaranta^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a,
F. Santanastasio^{a,b}

INFN Sezione di Torino ^a, Università di Torino ^b, Torino, Italy, Università del Piemonte Orientale ^c, Novara, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b},
C. Biino^a, A. Cappati^{a,b}, N. Cartiglia^a, F. Cenna^{a,b}, S. Cometti^a, M. Costa^{a,b},
R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b},
V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a,
M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b},
R. Salvatico^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, A. Da Rold^{a,b}, G. Della Ricca^{a,b},
F. Vazzoler^{a,b}, A. Zanetti^a

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak,
S. Sekmen, D.C. Son, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea

B. Francois, J. Goh³², T.J. Kim

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K.S. Lee, S. Lee, J. Lim,
S.K. Park, Y. Roh

Sejong University, Seoul, Korea

H.S. Kim

Seoul National University, Seoul, Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith,
S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea

D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Riga Technical University, Riga, Latvia

V. Veckalns³³

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

Z.A. Ibrahim, M.A.B. Md Ali³⁴, F. Mohamad Idris³⁵, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz³⁶, R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro

N. Raicevic

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

K. Bunkowski, A. Byszuk³⁷, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{38,39}, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

V. Golovtsov, Y. Ivanov, V. Kim⁴⁰, E. Kuznetsova⁴¹, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, A. Shabanov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia

M. Chadeeva⁴², P. Parygin, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin³⁹, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴³, L. Dudko, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia

A. Barnyakov⁴⁴, V. Blinov⁴⁴, T. Dimova⁴⁴, L. Kardapoltsev⁴⁴, Y. Skovpen⁴⁴

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev, S. Baidali, A. Iuzhakov, V. Okhotnikov

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences

P. Adzic⁴⁵, P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic⁴⁶, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, J.M. Vizán García

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

University of Ruhuna, Department of Physics, Matara, Sri Lanka

N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d’Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita⁴⁷, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, G.M. Innocenti, A. Jafari, P. Janot, O. Karacheban¹⁸, J. Kieseler, A. Kornmayer, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo¹⁵, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁸, A. Stakia, J. Steggemann, D. Treille, A. Tsiros, A. Vartak, M. Verzetti, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁴⁹, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

M. Backhaus, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Reichmann, C. Reissel, T. Reitenspiess, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁵⁰, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

National Central University, Chung-Li, Taiwan

T.H. Doan, C.M. Kuo, W. Lin, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

A. Bat, F. Boran, S. Cerci⁵¹, S. Damarcekin⁵², Z.S. Demiroglu, F. Dolek, C. Dozen, E. Eskut, G. Gokbulut, EmineGurpinar Guler⁵³, Y. Guler, I. Hos⁵⁴, C. Isik, E.E. Kangal⁵⁵, O. Kara, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵⁶, S. Ozturk⁵⁷, A. Polatoz, D. Sunar Cerci⁵¹, B. Tali⁵¹, U.G. Tok, S. Turkcpar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁵⁸, G. Karapinar⁵⁹, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁶⁰, O. Kaya⁶¹, Ö. Özçelik, S. Ozkorucuklu⁶², S. Tekten, E.A. Yetkin⁶³

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak, Y. Komurcu, S. Sen⁶⁴

**Institute for Scintillation Materials of National Academy of Science of Ukraine,
Kharkov, Ukraine**

B. Grynyov

**National Scientific Center, Kharkov Institute of Physics and Technology,
Kharkov, Ukraine**

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Ball, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold⁶⁵, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁶⁶, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash⁶⁷, A. Nikitenko⁸, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee¹⁵, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, U.S.A.

K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, U.S.A.

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, U.S.A.

A. Buccilli, O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, U.S.A.

D. Arcaro, T. Bose, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

Brown University, Providence, U.S.A.

G. Benelli, B. Burklee, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶⁸, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir⁶⁹, R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, U.S.A.

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, U.S.A.

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, U.S.A.

E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, San Diego, La Jolla, U.S.A.

J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, D. Olivito, S. Padhi, M. Pieri, V. Sharma, M. Tadel, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, U.S.A.

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, H. Mei, A. Ovcharova, H. Qu, J. Richman, D. Stuart, S. Wang, J. Yoo

California Institute of Technology, Pasadena, U.S.A.

D. Anderson, A. Bornheim, J.M. Lawhorn, N. Lu, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, U.S.A.

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, U.S.A.

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, U.S.A.

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. McDermott, N. Mirman, J. Monroy, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, U.S.A.

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon,

R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, F. Ravera, A. Reinsvold, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber

University of Florida, Gainesville, U.S.A.

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, U.S.A.

Y.R. Joshi, S. Linn

Florida State University, Tallahassee, U.S.A.

T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, C. Schiber, R. Yohay

Florida Institute of Technology, Melbourne, U.S.A.

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, U.S.A.

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, C. Mills, M.B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, U.S.A.

M. Alhusseini, B. Bilki⁵³, W. Clarida, K. Dilsiz⁷⁰, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁷¹, Y. Onel, F. Ozok⁷², A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, U.S.A.

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao

The University of Kansas, Lawrence, U.S.A.

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, U.S.A.

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, U.S.A.

F. Rebassoo, D. Wright

University of Maryland, College Park, U.S.A.

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, U.S.A.

D. Abercrombie, B. Allen, V. Azzolini, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, U.S.A.

A.C. Benvenuti[†], R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M.A. Wadud

University of Mississippi, Oxford, U.S.A.

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, U.S.A.

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, U.S.A.

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, U.S.A.

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D.M. Morse, T. Orimoto, A. Tishelman-charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, U.S.A.

S. Bhattacharya, J. Bueghly, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, U.S.A.

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, T. McCauley, F. Meng, C. Mueller, Y. Musienko³⁸, M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, U.S.A.

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, W. Luo, B.L. Winer

Princeton University, Princeton, U.S.A.

S. Cooperstein, G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully, Z. Wang

University of Puerto Rico, Mayaguez, U.S.A.

S. Malik, S. Norberg

Purdue University, West Lafayette, U.S.A.

A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, U.S.A.

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, U.S.A.

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

University of Rochester, Rochester, U.S.A.

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

Rutgers, The State University of New Jersey, Piscataway, U.S.A.

B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

University of Tennessee, Knoxville, U.S.A.

H. Acharya, A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A&M University, College Station, U.S.A.

O. Bouhali⁷³, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷⁴, S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, U.S.A.

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderov, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, U.S.A.

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

University of Virginia, Charlottesville, U.S.A.

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, U.S.A.

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, U.S.A.

J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gomber⁷⁵,
M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long,
R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W.H. Smith, N. Woods

†: Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 3: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 4: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- 6: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 7: Also at University of Chinese Academy of Sciences, Beijing, China
- 8: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 9: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 10: Also at Suez University, Suez, Egypt
- 11: Now at British University in Egypt, Cairo, Egypt
- 12: Also at Zewail City of Science and Technology, Zewail, Egypt
- 13: Also at Purdue University, West Lafayette, U.S.A.
- 14: Also at Université de Haute Alsace, Mulhouse, France
- 15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 17: Also at University of Hamburg, Hamburg, Germany
- 18: Also at Brandenburg University of Technology, Cottbus, Germany
- 19: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 21: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
- 23: Also at Institute of Physics, Bhubaneswar, India
- 24: Also at Shoolini University, Solan, India
- 25: Also at University of Visva-Bharati, Santiniketan, India
- 26: Also at Isfahan University of Technology, Isfahan, Iran
- 27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 28: Also at ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT, Bologna, Italy
- 29: Also at CENTRO SICILIANO DI FISICA NUCLEARE E DI STRUTTURA DELLA MATERIA, Catania, Italy
- 30: Also at Università degli Studi di Siena, Siena, Italy
- 31: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 32: Also at Kyung Hee University, Department of Physics, Seoul, Korea
- 33: Also at Riga Technical University, Riga, Latvia
- 34: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia

- 35: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 36: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 37: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 38: Also at Institute for Nuclear Research, Moscow, Russia
- 39: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
- 40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 41: Also at University of Florida, Gainesville, U.S.A.
- 42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 43: Also at California Institute of Technology, Pasadena, U.S.A.
- 44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 46: Also at University of Belgrade, Belgrade, Serbia
- 47: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy
- 48: Also at National and Kapodistrian University of Athens, Athens, Greece
- 49: Also at Universität Zürich, Zurich, Switzerland
- 50: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 51: Also at Adiyaman University, Adiyaman, Turkey
- 52: Also at Sirnak University, SIRNAK, Turkey
- 53: Also at Beykent University, Istanbul, Turkey
- 54: Also at Istanbul Aydin University, Istanbul, Turkey
- 55: Also at Mersin University, Mersin, Turkey
- 56: Also at Piri Reis University, Istanbul, Turkey
- 57: Also at Gaziosmanpasa University, Tokat, Turkey
- 58: Also at Ozyegin University, Istanbul, Turkey
- 59: Also at Izmir Institute of Technology, Izmir, Turkey
- 60: Also at Marmara University, Istanbul, Turkey
- 61: Also at Kafkas University, Kars, Turkey
- 62: Also at Istanbul University, Istanbul, Turkey
- 63: Also at Istanbul Bilgi University, Istanbul, Turkey
- 64: Also at Hacettepe University, Ankara, Turkey
- 65: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 66: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 67: Also at Monash University, Faculty of Science, Clayton, Australia
- 68: Also at Bethel University, St. Paul, U.S.A.
- 69: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 70: Also at Bingol University, Bingol, Turkey
- 71: Also at Sinop University, Sinop, Turkey
- 72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 73: Also at Texas A&M University at Qatar, Doha, Qatar
- 74: Also at Kyungpook National University, Daegu, Korea
- 75: Also at University of Hyderabad, Hyderabad, India